Decadal carbon discharge by a mountain stream is dominated by coarse organic matter

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Abstract

Rapid erosion in mountain forests results in high rates of biospheric particulate organic carbon (POC) export by rivers, which can contribute to atmospheric carbon dioxide drawdown. However, coarse POC (CPOC) carried by particles larger than ~1 mm is rarely quantified. In a forested pre-Alpine catchment, we measured CPOC transport rates and found that they increase more rapidly with water discharge than fine POC (<1mm) and dissolved organic carbon (DOC). As a result, decadal estimates of CPOC yield of 12.3±1.9 tC km^{-2}yr^{-1} are higher than for fine POC and DOC, even when excluding 4 extreme flood events. When including these floods, CPOC dominates organic carbon discharge (~80%). Most CPOC (69%) was water-logged and denser than water, suggesting CPOC has the potential to contribute to long-term sedimentary burial. Global fluxes remain poorly constrained, but if the transport behavior of CPOC shown here is common to other mountain streams and rivers then neglecting CPOC discharge could lead to a large underestimation of the global transfer of biospheric POC from land to ocean.

Introduction

Erosion of particulate organic carbon (POC) from the terrestrial biosphere and its transport by rivers redistributes nutrients and can contribute to atmospheric carbon dioxide drawdown (Berner 1982, Stallard 1998, Battin et al. 2008, Galy et al. 2015). High rates of physical erosion in mountain catchments result in elevated rates of fine POC discharge (FPOC, particles >0.2-0.7 µm and <1 mm), with biospheric FPOC ($FPOC_{biosphere}$) yields >10 tC km^{-2}yr^{-1} (Hilton et al. 2012, Goñi et al., 2013, Smith et al. 2013, Galy et al. 2015). As a result, mountain rivers can contribute significant amounts of $FPOC_{biosphere}$ to large rivers, lakes and the oceans (Stallard 1998, Hilton et al. 2012, Galy et al. 2015). This carbon, derived from atmospheric carbon dioxide (CO_2) via photosynthesis, is often transported along with large volumes of clastic sediment (Hilton et al. 2012). High sediment accumulation rates in depositional settings can increase the burial efficiency of $POC_{biosphere}$ and promote the drawdown of atmospheric CO_2 over geological timescales (Berner 1982, Kao et al. 2014, Galy et al. 2015).

Despite this recognition, the organic carbon (OC) transported as coarse particulate organic matter (CPOM, particles >1 mm) remains poorly constrained, mainly because it is challenging to measure. CPOM can range in size from leaves to entire trees and is not captured by typical river water sampling methods (e.g. Goñi et al., 2013, Smith et al. 2013, Hilton et al. 2015), while it is transported episodically during large floods, when it is difficult to work in river channels (West et al. 2011, Wohl 2013, Kramer and Wohl, 2014). CPOM also contributes to ecosystem functions because it typically contains around 50% carbon by weight and can form the basis of the food chain in many streams (Fisher and Likens 1973). In addition to contributing to carbon and nutrient transfers in rivers, large wood (LW), consisting of CPOM with lengths exceeding 1 m, can impact stream morphology and hydraulics, while providing shelter for in-stream fauna and affecting breeding grounds (Wohl 2013).

A significant challenge remains to accurately measure coarse POC (CPOC) transport in rivers across the full size range of CPOM, while linking CPOC transfer to hydrodynamic conditions in rivers. Only by doing so, CPOC yields (tC km^{-2} yr^{-1}) can be accurately quantified. In addition, CPOC eroded from the biosphere is often thought to float (West et al. 2011), suggesting that it could be more susceptible to oxidation upon its delivery to floodplains (Fisher and Likens 1973), lakes and reservoirs (Seo et al. 2008), and the oceans (West et al. 2011). However, water-logged woody debris, with a density higher than water, is a component of $FPOC_{biosphere}$ in large river systems (Bianchi et al. 2007; Hilton et al. 2015). The amount of water-logged CPOC discharged by mountain rivers remains unknown. Here, we use detailed measurements of CPOM transport in the Erlenbach, a 0.7 km^2 catchment in the Swiss pre-Alps. While small, it has geomorphic, climatic and ecological characteristics representative for forested mountain headwater streams in a temperate climate (Schleppi et al. 1999, Smith et al. 2013).

Methods

The Erlenbach is a steep (11% slope) mountain stream with step-pool morphology and drains 0.7 km^2 in the Swiss Prealps (LAT47.045707°, LON8.708844°) (Fig. 1). The mean annual air temperature is ~4.5°C and the mean annual precipitation is ~2300 mm. Approximately 40% of the total catchment area is covered by alpine forest, mainly comprising Norway Spruce (*Picea abies*) and European Silver Fir (*Abies alba*) (Schleppi et al. 1999), and a small amount of logging has been done in the upper catchment over the past ten years. The remaining 60% of the catchment is covered by wetland and alpine meadows. A well-developed riparian zone is generally lacking and active landslide complexes along the channel lead to strong channel-hillslope coupling typical of many steep mountain catchments. Both DOC and FPOC fluxes have been previously determined (Hagedorn et al. 2000, Smith et al. 2013). Importantly, the FPOC has been partitioned into that derived from the terrestrial biosphere ($FPOC_{biosphere}$) and that from rock-derived OC using stable carbon isotopes, nitrogen to carbon ratios and radiocarbon (Smith et al. 2013).

We use CPOM data sampled with three different methods (Supplementary Material), each of which is suitable for a different water discharge range (Turowski et al. 2013). All sampling locations were within 30 m of a permanently installed gauge measuring water discharge (Q_w, l s^{-1}) at ten minute intervals (Rickenmann et al. 2012). At low Q_w (1 l s^{-1} to 1000 l s^{-1}, with most samples <250 l s^{-1}), we used Bunte traps (Bunte et al. 2007). These are metal frames placed on the stream bed, to which a net with 6 mm meshing is attached. At intermediate Q_w (200 l s^{-1} to 1500 l s^{-1}, with most samples >400 l s^{-1}), we used basket samplers (Rickenmann et al. 2012), consisting of metal cubes with 1 m edges and walls and floor made of metal mesh with 10 mm holes. They automatically move into the flow when Q_w exceeds a pre-defined threshold value and when bedload transport is recorded. Both traps and baskets sample the entire flow depth with near 100% efficiency (Rickenmann et al. 2012; Turowski et al. 2013).

Woody material in the basket and trap samples was separated from clastic material in the field and weighed. Basket samples from 2011-2013 were separated into floating and sinking fractions in the field by dropping them into a water-filled bucket. Subsequently, the material was dried for 24 hours at 80°C, and the dry mass was obtained.

Diameter and length of large woody debris trapped in a retention basin after two extreme events (1995, 2010) complements the data at high Q_w (>5000 l s^{-1}). Masses were calculated assuming a cylindrical shape and a dry density of 410 kg/m^3, which is typical for the Norway Spruce (*Picea Abies*) that is common in the catchment. The three methods were made comparable by using distributions of particle masses (Turowski et al. 2013). CPOC was calculated from CPOM using the mean OC content of 47.8±3.8% (±standard deviation) measured of 37 randomly drawn sub-samples.

Results

The transport rate of CPOC (kgC s^{-1}) was positively correlated with Q_w and well described by a power law rating curve (r^2=0.87, Fig. 2A). CPOC transport increases much more rapidly with increasing Q_w (rating curve exponent β=4.14±0.19) than DOC (r^2=0.98, β=1.17±0.04) and $FPOC_{biosphere}$ (r^2=0.88, β=1.90±0.10). The data confirm that high river power is needed to mobilize and transport CPOC (West et al. 2011, Wohl 2013). The relationship is consistent with the difference between bedload and suspended load transport rates in the Erlenbach (cf. Turowski et al. 2009, Smith et al. 2013), suggesting that CPOC is travelling as part of the bedload. This interpretation is supported by the observation that large fractions (mean: 69%, median: 78%) of the CPOM were water-logged and denser than water, especially at high Q_w

(Fig. 2B). Water-logging likely occurs during storage of CPOM in log jams in the stream, or within saturated soil and litter on the hillslopes.

To estimate the decadal rate of CPOC discharge, we fitted a linear regression in double-logarithmic space to obtain a rating curve. The data points obtained from the retention basin material were not included in the regression, but lie close to the rating curve at high Q_w. We used additional data from 2013, which resulted in a different rating curve than previously published (cf. Turowski et al. 2013). The rating curve was integrated over 31 years of Q_w measurements. During this period, four exceptional flood events hit the catchment (Turowski et al. 2009), with peak Q_w > 9000 l s^{-1} and return periods exceeding 20 years. Not accounting for these four floods, the background CPOC yield was 12.3±1.9 tC $km^{-2}yr^{-1}$. Uncertainties were derived from analytical errors of the rating curve fits. The exceptional floods delivered between 331 tC km^{-2} and 1066 tC km^{-2}, with an average of 585 tC km^{-2}. These values are lower than the 6300-19,100 tC km^{-2} of LW carbon (LWC) delivered to the ocean during typhoon Morakot in Taiwan (West et al. 2011), but higher than the 10-24 tC km^{-2} of LWC delivered from the Upper Rio Chagres, Panama, in a rain storm (Wohl and Ogden 2013). In total, the four floods delivered 2338±1609 tC km^{-2}, or 75.4±51.9 tC $km^{-2}yr^{-1}$. When added to the background rate, the total average CPOC discharge estimate is 87.7±51.9 tC $km^{-2}yr^{-1}$. Exceptional flood events appear to be even more important for CPOC than for $FPOC_{biosphere}$ (Hilton et al. 2012), which results from the steep relationship between CPOC transport rate and Q_w (Fig. 2A; Supplementary Material, Fig. S1).

The background CPOC yield (12.3±1.9 tC $km^{-2}yr^{-1}$) from the Erlenbach is a significant catchment-scale carbon transfer (Hilton et al. 2012, Galy et al., 2015) and on its own is comparable to the upper range of estimates of $FPOC_{biosphere}$ yields from temperate and tropical active mountain belts (Fig. 3). Other carbon transfers from the Erlenbach, obtained using the same methods on previously collected data (Hagedorn et al. 2000, Smith et al. 2013), are lower than CPOC transfer, with a DOC yield of 11.3±0.0 MgC $km^{-2}yr^{-1}$, and a $FPOC_{biosphere}$ yield of 10.7±0.1 MgC $km^{-2}yr^{-1}$. The background CPOC transfer thus represents ~36% of the decadal biospheric OC discharge by this catchment. Inclusion of the exceptional events raises CPOC transfer to up to ~80% of the total OC (TOC) discharge (Fig. 3). We can assess the sustainability of OC export by comparing it to the net primary production (NPP) of ~740 MgC $km^{-2}yr^{-1}$ in the Erlenbach catchment (Supplementary Material). The background rate of CPOC discharge is ~1.7% of this NPP and is sustainable, in agreement with a global compilation of river $FPOC_{biosphere}$ yields (Galy et al. 2015). However, extreme events may severely deplete the biosphere stock of carbon. The CPOC discharge during a single event appears to have the potential to exceed the catchment's yearly production; on decadal timescales our data suggests that exceptional events discharge~10% of the NPP.

Discussion

The contribution of CPOC to carbon discharge by rivers is not typically quantified, and a direct comparison with data from other catchments remains challenging. Notwithstanding, it has been calculated that LWC alone contributes at least 10% and up to 35% of the total carbon yields in mountain rivers with catchment areas up to 2000 km^2 (Supplementary Material, Fig. S2) (Seo et al. 2008). CPOM particles smaller than LW down to sizes of 1 mm were not considered in that study, but dominate CPOC in the Erlenbach (cf. Turowski et al. 2013). Based on the Erlenbach's size, its $FPOC_{biophere}$ and LWC yields are similar to those observed in other mountain regions in the world (Supplementary Material, Fig. S2). $FPOC_{biosphere}$ yields are known to be strongly linked to physical erosion rate (Fig. 3) (Galy et al. 2015), and high yields are observed in active mountain belts in temperate and tropical settings (Hilton et al. 2012). In line with this, estimates of LWC transfer in Taiwanese catchments are larger than for the Erlenbach (West et al. 2011). Therefore, we propose that the often neglected CPOC fraction is a significant component of $POC_{biosphere}$ export from forested mountain catchments.

To make a tentative first assessment of the global significance of CPOC transport, we assume that the Erlenbach catchment is representative for temperate mountain forests, which cover a total area of 1.2×10^6 km^2 worldwide (Sands 2005). While the climatic, geomorphic, and ecological characteristics of the Erlenbach support that assumption, its physical erosion rate is high (Fig. 3). Without more measurements of CPOC transport (Fig. 1) and estimation of CPOC yields (Fig. 3), a global CPOC discharge estimate remains poorly constrained. Based on the Erlenbach background CPOC yield over 31 years (12.3 ± 1.9 tC $km^{-2}yr^{-1}$), the global CPOC discharge from temperate mountain forest catchments could be ~15 MtC yr^{-1}. This is ~10% of the recent estimate of global $FPOC_{biosphere}$ discharge to the oceans by rivers of 157+74/-50 MtC yr^{-1} (Galy et al. 2015). If extreme floods are included, CPOC discharge from temperate mountain forests could be even higher (Fig. 3). Global CPOC discharge would further increase if boreal, subtropical and tropical mountain forests were considered. We are aware that these estimates are based on extrapolation from a very small continental area and absolute flux has large uncertainty. Nevertheless, the magnitude of the estimate demonstrates the need to better quantify CPOC transfer rates in mountain rivers and track its conveyance through large river systems.

Little is known about the onward fate and routing of CPOC through large rivers. On average ~69% of the CPOM transported by the Erlenbach was water-logged with a density greater than water (Fig. 2B). If this observation applies to other temperate streams where channel morphology can promote transient storage of CPOM, sampling with drift nets may have missed large fractions of CPOM travelling near the stream bed. Perhaps more importantly, water-logged CPOM may have a different fate in fluvial networks than if it were to float. During transport in steep channels, water-logged CPOM may be ground by gravel bedload, reducing its size. The size reduction of CPOM by bedload grinding is poorly understood, but the observed magnitude of the CPOC flux means it can be an important in-stream source of $FPOC_{biosphere}$ (Hilton et al. 2012).

Furthermore, a high density of CPOM may promote its burial potential in sedimentary basins. If water-logged CPOM is delivered to depositional environments as part of the bedload it can rapidly accumulate in sedimentary deposits. Observations of large terrestrial organic debris in deep sea turbidites in Indonesia (Saller et al. 2006), woody clasts and plant debris in modern deep sea sediments offshore Taiwan (Kao et al. 2014) and mountain rivers draining the west coast of the US (Leithold and Hope, 1999) all suggest CPOC can be delivered to deep marine settings. We substantiate these arguments by estimating the contribution of CPOC to TOC in exhumed turbidite sequences in the Apennines, Italy (Supplementary Material). Despite estimated transport distances of up to 300 km offshore, CPOC was buried and preserved for 14 Ma and represents ~10% of the TOC. Water-logged woody debris can be delivered by mountain rivers as CPOC (Fig. 2B), and its presence may enhance the efficiency of carbon burial and associated atmospheric CO_2 sequestration by erosion of mountain belts (Kao et al. 2014, Galy et al., 2015).

Conclusions

CPOC is the dominant form of OC discharge by the Erlenbach over decadal time scales, increasing the carbon loss from the biosphere by ~250% over DOC and $FPOC_{biosphere}$. The majority of CPOC may be transported in water-logged CPOM as part of the bedload. Our observations provide new impetus to study the production, transfer and routing of CPOC from mountain headwaters, and subsequently through large river systems to fully assess the net impact of erosion on the global carbon cycle (Battin et al. 2008, Hilton et al. 2012, Hilton et al. 2015, Galy et al. 2015). Due to anthropogenic CO_2 emissions and global warming, extreme precipitation events may become more frequent (Rajczak et al. 2013), causing an increased number of extreme floods. CPOC transport exhibits a much stronger dependency on water discharge than FPOC and DOC transport (Fig. 1), and could therefore become more important for carbon budgets of mountain streams in the coming decades. This may have implications for forest management, food availability in stream ecosystems and carbon mobilization by erosion of the terrestrial biosphere.

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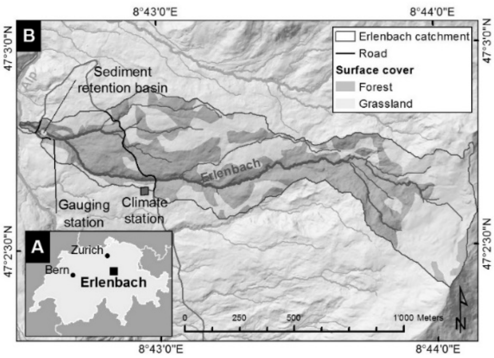

Fig. 1: Location of the Erlenbach catchment in Switzerland (A) and map of the catchment (B).

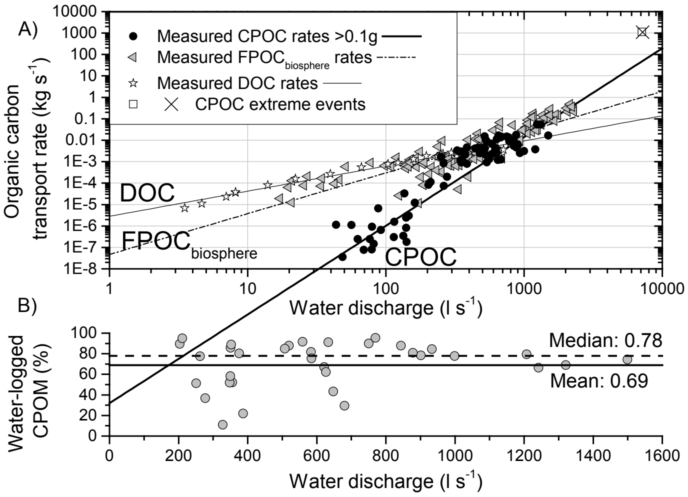

Figure 2A: Coarse Particulate Organic Carbon (CPOC) transport rate (kgC s^{-1}) as a function of water discharge (l s^{-1}) for the Erlenbach study catchment (circles). Also shown are published measurements of dissolved organic carbon (DOC) (Hagedorn et al. 2000) and fine biospheric particulate organic carbon ($FPOC_{biosphere}$) transfer (Smith et al. 2013). Data are fit with power law rating curves for CPOC (thick solid line, exponent β = 4.14±0.19), $FPOC_{biosphere}$ (dashed line, β = 1.90±0.10) and DOC (fine solid line, β = 1.17±0.04). CPOC data from extreme events in 1995 and 2010 (box, cross) support the rating curve fit.

Figure 2B: Percent of water-logged coarse particulate organic matter (CPOM) at the time of collection. Mean (69%) and median (78%) of 35 basket samples are indicated by the solid and the dashed line, respectively. Low values at water discharges <600 l s^{-1} arose from autumn samples with small absolute mass consisting mainly of fresh leaves. Summed over all samples, water-logged CPOM contributed 76% to the total dry mass.

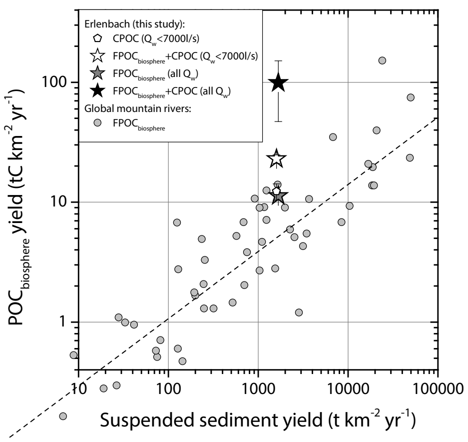

Figure 3: Literature data of biospheric particulate organic carbon ($POC_{biosphere}$) yield (tC km^{-2}yr^{-1}) plotted against suspended sediment yield (t km^{-2}yr^{-1}) for global rivers (grey circles) with fitted relationship (dashed line) (Galy et al. 2015). The Erlenbach does not show exceptional $FPOC_{biosphere}$ yields for its suspended sediment yield (grey star). Inclusion of coarse POC (CPOC) for the Erlenbach, which is not available for the other catchments, increases carbon export by an order of magnitude (black and white stars).

Author contributions

JMT collected and analyzed the Erlenbach CPOM samples and performed calculations and statistical analyses. RGH compiled data displayed in Fig. 3. RS collected and analyzed samples from turbidite deposit and estimated their CPOC fraction. JMT and RGH co-wrote the paper with additional inputs by RS.

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